NORTH CAROLINA
Department of Transportation









NC MOVES 2050

Drivers and Opportunities

Environment and Climate Change Resilience

June, 2019

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EXECUTIVE SUMMARY

Environmental Hazards – Executive Summary

North Carolina requires a safe and reliable operating transportation system to support its population and economic growth and be resilient to future environmental hazards.

Hazard Impacts (Damage and Disruption). Environmental hazards pose varying risks to roads and bridges across the state. Coastal flooding from hurricanes and sea level rise, inland flooding, and winter storms pose the greatest risks today. Coastal flooding is projected to be a significant risk moving forward. A good amount of information is known regarding those locations historically impacted. For some hazards, such as flooding, changes in the likelihood of occurrence and the emerging impacts are being learned in real-time. Data is increasingly becoming available, collected, and digitized. This data should be mined for a risk-based evaluation that can target smart project prioritization and investment decisions to inform both NC Moves 2050 and NCDOT Transportation Asset Management Plan (TAMP).

Emergency Response. NCDOT has a strong working relationship with North Carolina's emergency management staff and continues to actively pursue innovative technologies for communicating disruptions with the public in real-time. This is an area that needs continued leadership support to remain strong, regardless of whether an event has happened.

Resilience Strategies. Assessing environmental risks to roads and bridges, along with quantifying the rippling consequences to the communities, can allow NCDOT to determine effective resilience strategies that support smart investments. A risk-based analysis that supports program solutions can inform NC Moves 2050 strategic recommendations and decisions for an increasingly resilient system.

INTRODUCTION

Understanding Environmental Hazards

Focusing on highways and bridges, this paper:

- Reviews the locations in North Carolina currently susceptible to environmental hazards;
- Presents the projected changes in these hazards (as applicable);
- Summarizes findings from a series of interviews regarding state of practice and existing vulnerabilities;
- Examines current preparedness plans in terms of building a more resilient transportation system.

Hurricane Ophelia rains flood the Davis community in Carteret County; Source: NOAA

Bat cave mudslide on NC-9 (2018); Source: NCDOT

How Does Resilience to Environmental Hazards Link to NC Moves 2050

Meeting Federal and State Requirements

- NC Executive Order 80 (10/29/2018), requires "cabinet agencies to evaluate the impacts of climate change on their programs and operations and integrate climate change mitigation and adaptation practices into their programs and operations…cabinet agencies shall integrate climate adaptation and resiliency planning into their policies, programs, and operations…"
- In 23 CFR 515.7.c.1-6, FHWA requires states to establish a process for developing a risk management plan (that includes current and future environmental hazards).

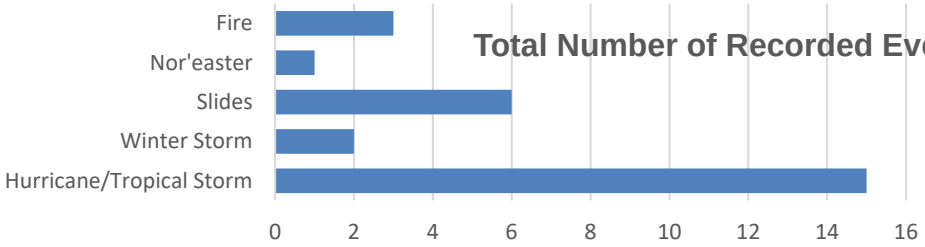
Focus Investments towards a Resilient Future

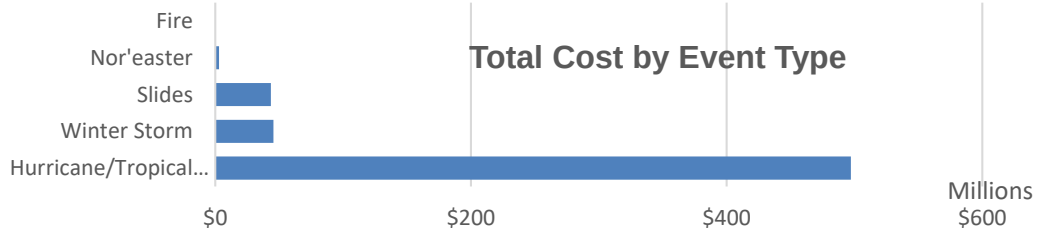
- Understanding which NCDOT assets are at risk and are critical to the community builds a roadmap for focusing mitigation investment.
- Roadways and bridges that are resilient reduce NCDOT maintenance and repair costs over the life cycle of the asset.
- Understanding which hazards are problematic and which man-made stressors will amplify the impact leads to better informed decisions (e.g., should urban development be encouraged in an area where roadways already flood from runoff).
- The safety of NCDOT travelers is directly dependent on traversable emergency evacuation routes, sensitivity of roads and bridges to a hazard event, adequate driving visibility, and effective communication of dangerous driving conditions.

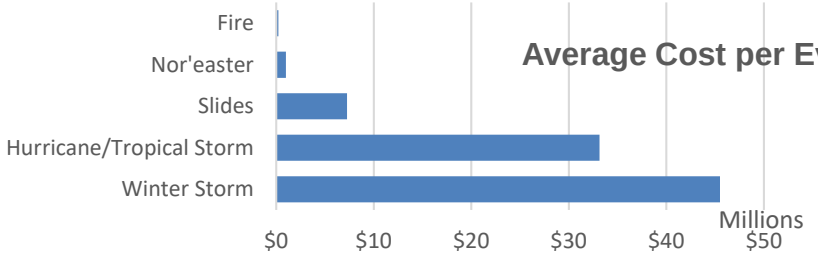
WHERE ARE WE TODAY?

NCDOT Federally Declared Events

Since 2004, Hurricane and Tropical Storms are responsible for 84% of the expenditures of declared events recorded by NCDOT, representing just over half of the 28 events.[5] Declared winter storms average to be the most expensive events, though this is due to the expensive 2014 storm.[5]







Federally Declared Events Expenditures (2004 to 2018)*	
Event	**Expenditures**
Hurricane Isabel	$39,831,800
Hurricane Frances	$16,349,400
Hurricane Ivan	$61,462,800
Hurricane Katrina	$58,800
Hurricane Ophelia	$3,162,700
Hurricane Ernesto	$1,967,700
Nor'easter 2006	$2,958,700
Rockslide Haywood Co	$16,493,200
Tropical Storm Ida	$1,459,600
Tropical Storm Nicole	$1,144,200
Forrest Fire Activity	$316,300
Tropical Storm Hanna	$2,068,800
Dec 2009 Winter Storm	$14,482,600
Hurricane Earl	$23,000
April 2011 Tornado	$6,523,100
Simmons Rd Fire	$2,800
Hurricane Irene	$44,214,400
Hurricane Sandy	$32,326,200
Jan 2013 Mudslides	$2,983,700
Avery/Wilkes Mudslides	$4,427,800
July 3-13 2013 Slides	$11,538,400
July 27 2013 Slides	$5,494,600
March 2014 Winter Storm	$31,016,500
Hurricane Joaquin	$1,471,500
Hurricane Matthew	$199,842,200
NC Party Rock Fire	$109,500
TS Alberto/Western Mudslides	$5,553,500
Hurricane Florence	$91,751,900

**Based on recorded data as of 2/2019. This does not include the full expenditures for Hurricane Florence or expenditures relating to Hurricane Matthew.*

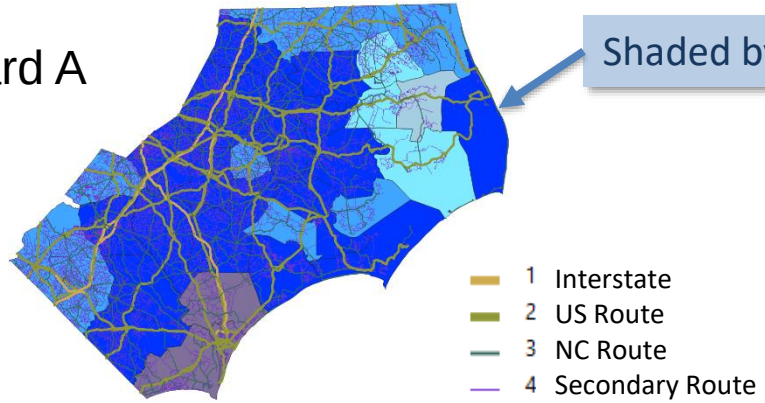
Source: Based on NCDOT Records[5]

Where are we Today?

How to Read the Annual Occurrence Figures

Example Figure of Annual Occurrence of a Threat (Hazard A)

Hazard A



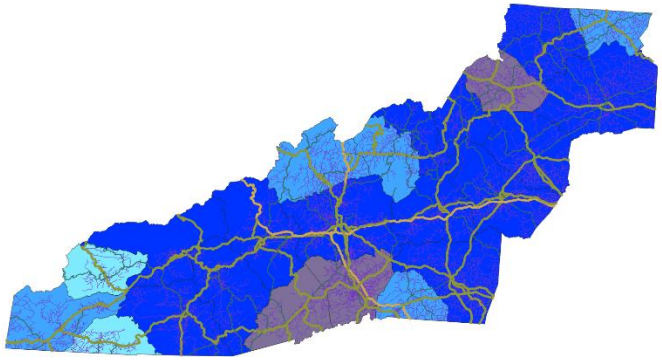
How do I interpret the "annual occurrence" legend?

Annual Occurrence

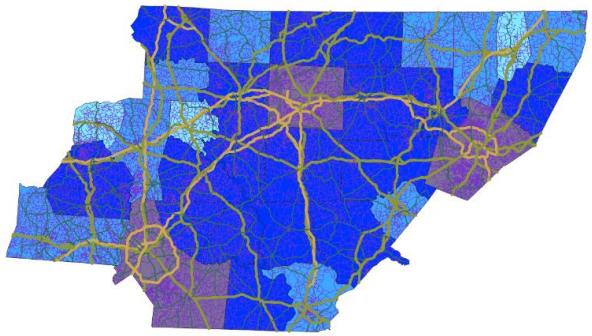
For time period of record, a hazard event has not been recorded in this county	0	
10% to less than 20% chance of occurring in any given year	0.1 to 0.2	
20% to less than 50% chance of occurring in any given year	0.2 to 0.5	
50% to less than 100% chance of occurring in any given year	0.5 to 1	
	1 to 3	Occurs 1 to less than 3 times a year, on average
	3 to 7	Occurs 3 to less than 7 times a year, on average
	7 to 20	Occurs 7 to less than 20 times a year, on average

Where are we Today?

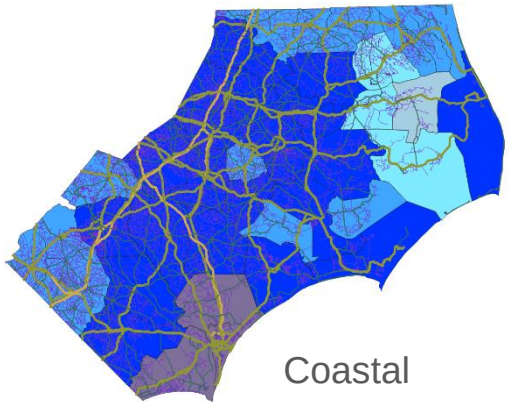
Hazard: Floods and Rainfall



Mountain

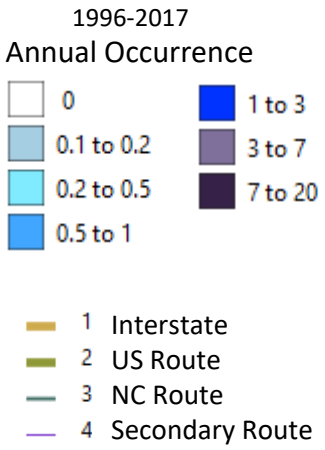


Piedmont



Coastal

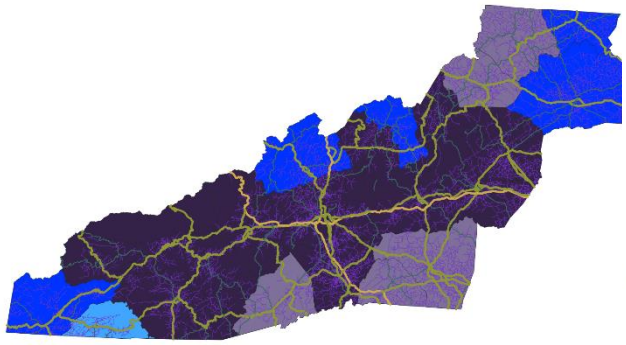
- Floods occur often across the state, at least once a year or more on average.[21]
- Heavy rains can trigger flashfloods that create scour issues for bridges (i.e., sediment such as sand or gravel is pulled away from bridge piers or abutments leaving scour holes that affect the integrity of the bridge).[19]
- Heavy rains can trigger mudslides and landslides, closing portions of the highway system (e.g., I-40).[1,4]
- 183 landslides from 1990 to 2016 damaged 79 roads, 89% occurring where slope modifications by humans were contributing factors (majority being fill failures).[2]
- Road damage and road closures have increased maintenance costs and caused significant delays to travelers.[5]

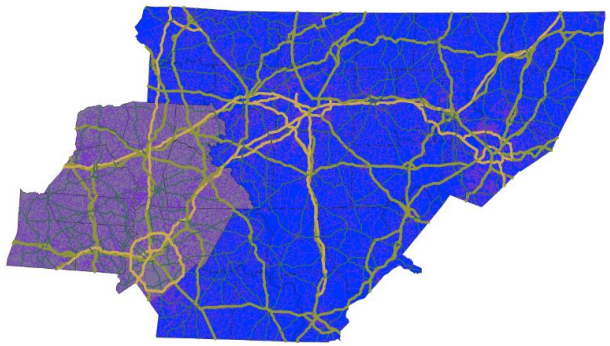


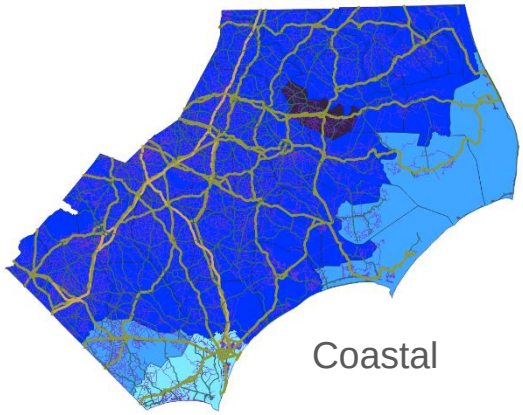
Source: WSP developed GIS maps based on data provided in NCDPS Enhanced Mitigation Plan[21] and NCDOT on-line NCRouteArcs GIS data[23].

Where are we Today?

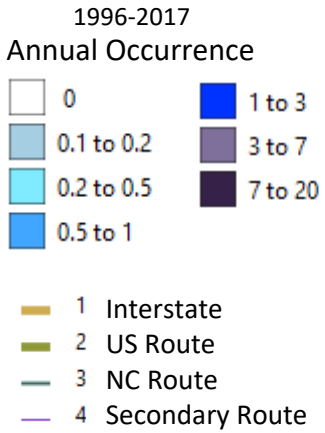
Hazard: Winter Storms


Mountain


Piedmont


Coastal

- Winter storms occur often, at least once a year or more on average.
- Using brine on bridges for winter storm safety can shorten the life of a bridge with joints.[19]
- Problematic winter storm locations (where pre-staging of resources occurs):[3]
  - Turner Grade on I-77
  - Saluda Grade on I-26
  - Gateway to the Mountains on I-40
- Can be problematic to secure contract support of snow removal if NCDOT requires additional support.[5]

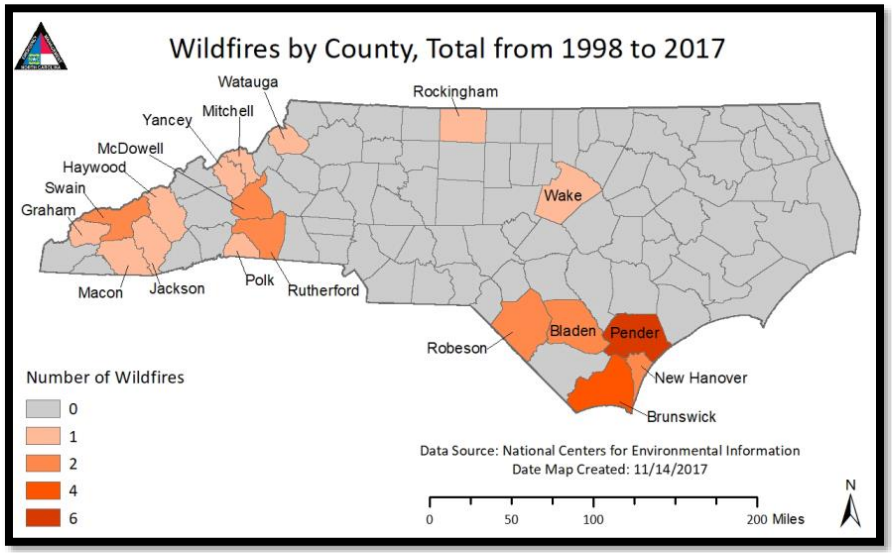


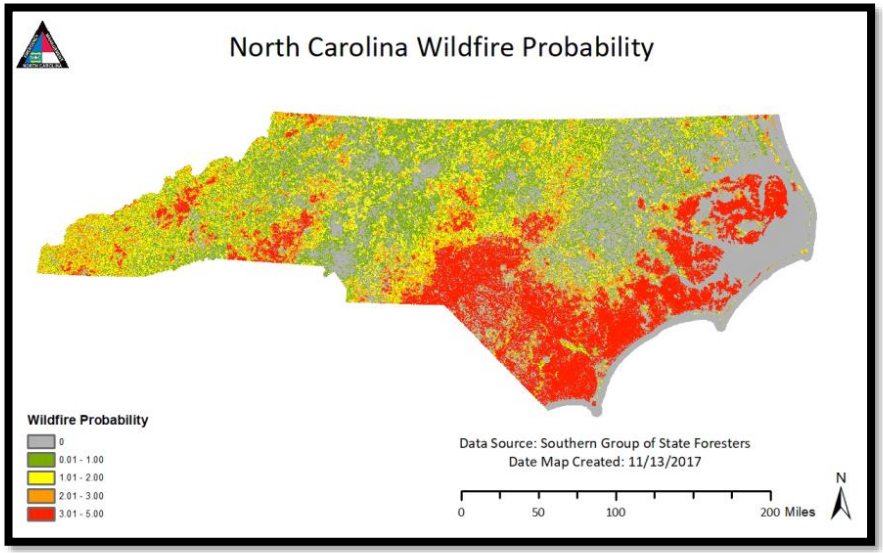
Source: WSP developed GIS maps based on data provided in NCDPS Enhanced Mitigation Plan[21] and NCDOT on-line NCRouteArcs GIS data[23].

Where are we Today?

Hazard: Wildfires

- Wildfires have historically occurred in isolated counties in the Mountain and Coastal regions of North Carolina.[21]
- Wildfires are particularly problematic in the southern portion of the Coastal region, though not considered a significant impact on transportation.[5]

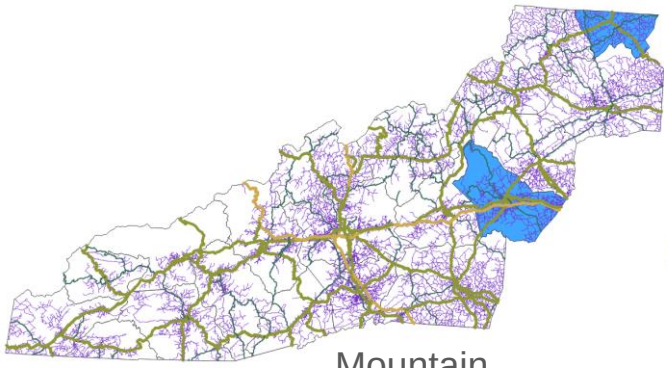


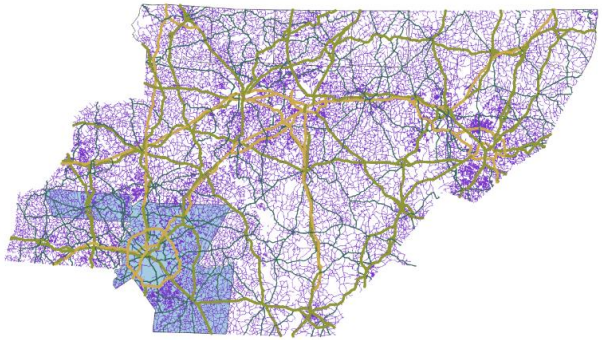


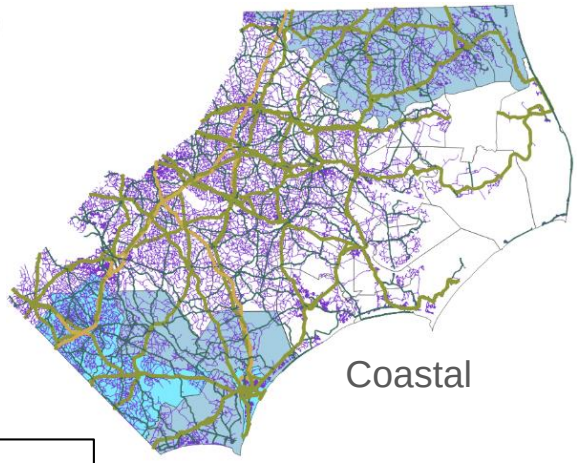
Source: NCDPS Enhanced Mitigation Plan[21]

Where are we Today?

Hazard: Heat Events


Mountain


Piedmont


Coastal

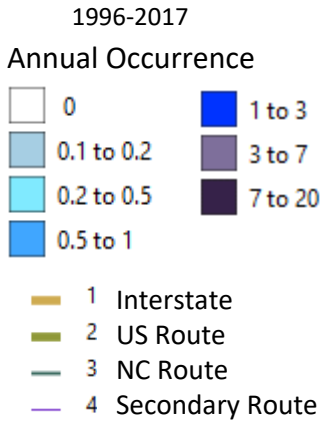
From 1996 to 2017, heat events which represent a day in which the heat index (combination of heat and humidity[22]) is considered dangerous:

- 61 of the 100 N.C. counties have experienced at least 1 heat event.[21]
- 20 N.C. counties have experienced at least 3 heat events. [21]
- Only one county in the coastal region, Robeson, experienced 5 heat events. [21]

Impacts associated with heat events

- Create health issues for construction workers
- Impact bridge and pavement joints

(Note: during our interviews, these impacts were not identified as already causing problems)

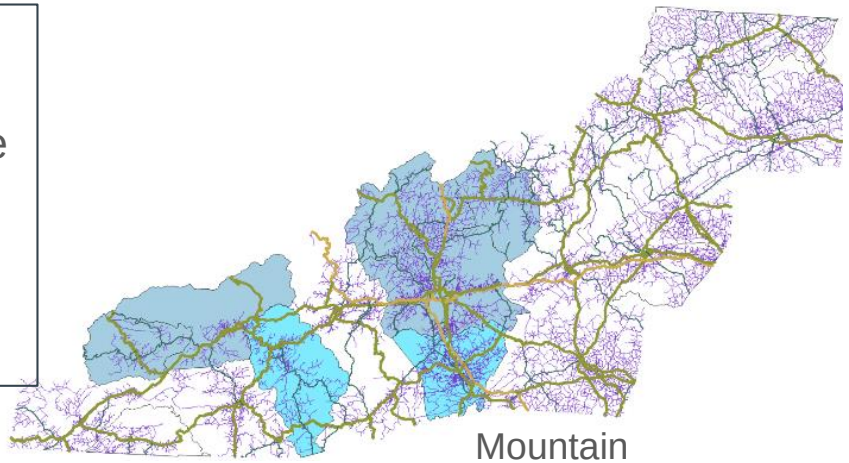


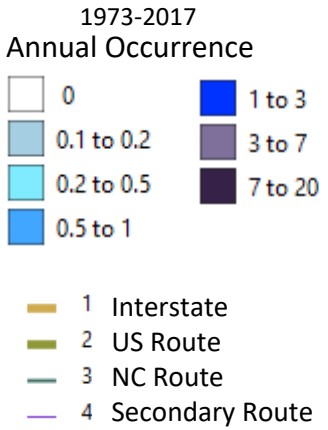
Source: WSP developed GIS maps based on data provided in NCDPS Enhanced Mitigation Plan[21] and NCDOT on-line NCRouteArcs GIS data[23].

Where are we Today?

Hazards: Earthquake

Earthquakes have historically occurred in isolated counties in the mountain region, with an average frequency of up to once every 13 years.[21]





Source: WSP developed GIS maps based on data provided in NCDPS Enhanced Mitigation Plan[21] and NCDOT on-line NCRouteArcs GIS data[23].

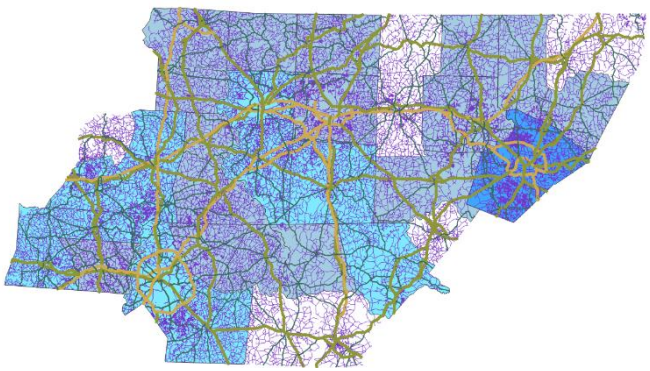
Earthquake of 5.0 magnitude or larger (1900-2018)

Source: USGS[24]

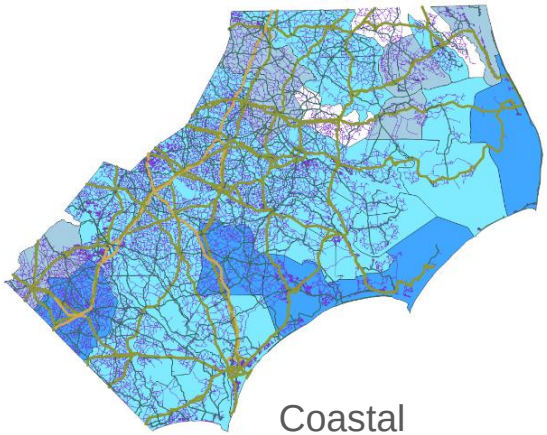
Where are we Today?

Hazard: Tornadoes

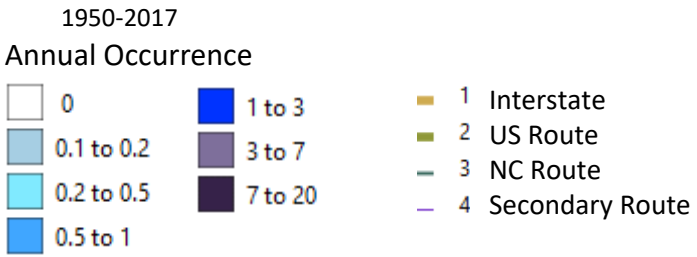
- From 1950 to 2017, tornadoes have occurred at least once in most N.C. counties, with greater frequency in the piedmont and coastal regions.[21]
- The piedmont region experiences tornadoes, with Wake County exposed to 35 tornadoes from 1950 to 2017.[21]
- Some counties in the coastal region have a tornado event almost every 1-2 years.[21]



Piedmont



Coastal



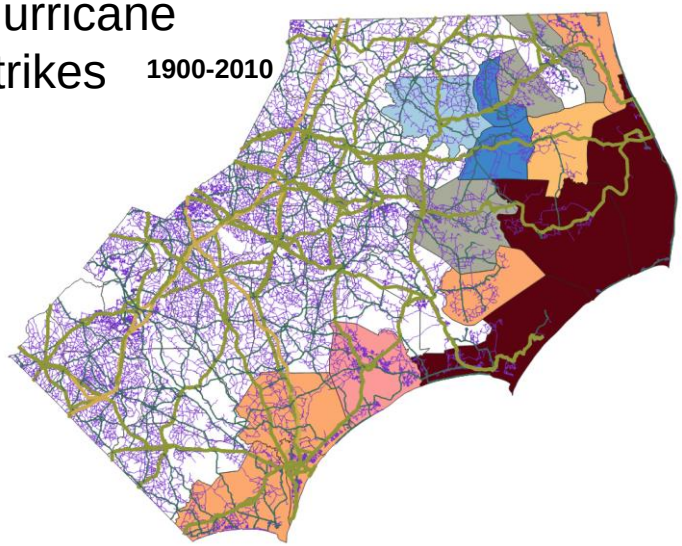
Source: WSP developed GIS maps based on data provided in NCDPS Enhanced Mitigation Plan[21] and NCDOT on-line NCRouteArcs GIS data[23].

Where are we Today?

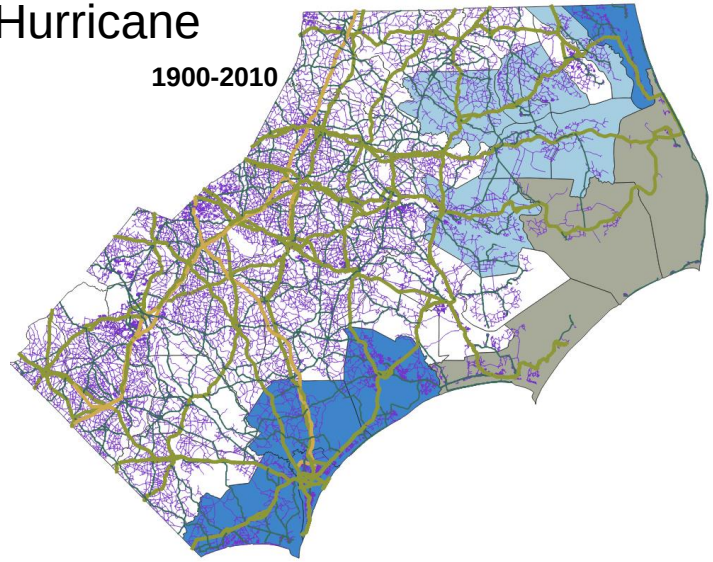
Hazard: Hurricanes

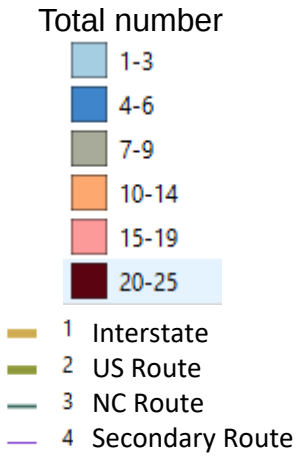
- North Carolina is more susceptible to direct hurricane strikes than much of the East Coast, with hits most likely in September and October. A hurricane strike is when the hurricane makes direct landfall or if the hurricane did not make landfall but did produce hurricane force winds on land (NOAA). [7]
- The North Carolina coast line is likely to experience a hurricane every 5 to 7 years, with a major hurricane (i.e., category 3 or higher) occurring about every 20 years. [7]
- A greater number of hurricanes (and major hurricanes) have hit the central to northern coastline of the state compared to the southern coastline. [7]
- During Hurricane Florence I-95 was closed between mile markers 17 & 22 in Lumberton and between mile markers 46 & 56 in Fayetteville due to major flooding, as was I-40 between mile markers 387 & 389 along the Pender/Duplin county line, at mile marker 398 in Burgaw, and at mile marker 413 in Castle Hayne.[1,6, 18]
- During Hurricane Florence, New Hanover and Brunswick counties were nearly cutoff. Town Creek flooded causing New Hanover to be only accessible from the north and Brunswick to be only accessible from the south both utilizing extensive detours. [31]

Hurricane strikes **1900-2010**



Major Hurricane strikes **1900-2010**



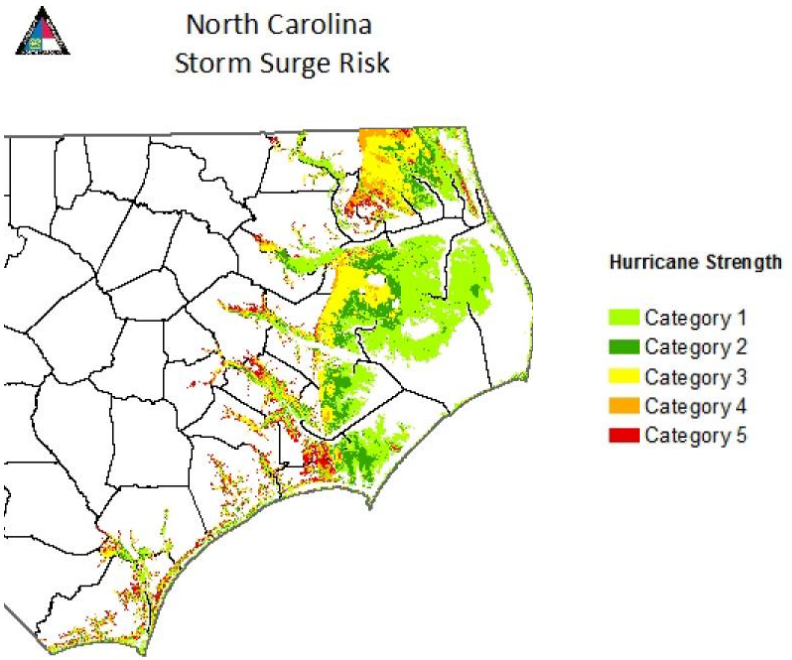


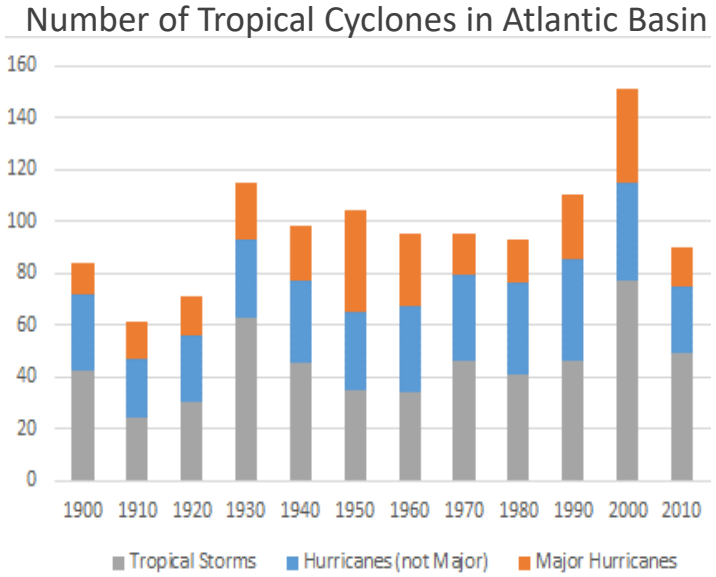
Where are we Today?

Source: WSP developed figures using event data provided by NOAA NHC[28] and NCDOT NCRouteArcs GIS data[23].

Storm Surge Risk

- Storm surge is the ocean water level above the astronomical tide caused by hurricane winds and is a function of storm intensity, forward speed, size, angle of approach, central pressure and shape/characteristics of the coastline.[20]
- During a hurricane, storm surge can cause significant damage to infrastructure and life.
- Scientists observe an upward trend in North Atlantic hurricane activity since the 1970s (see figure below).[8]



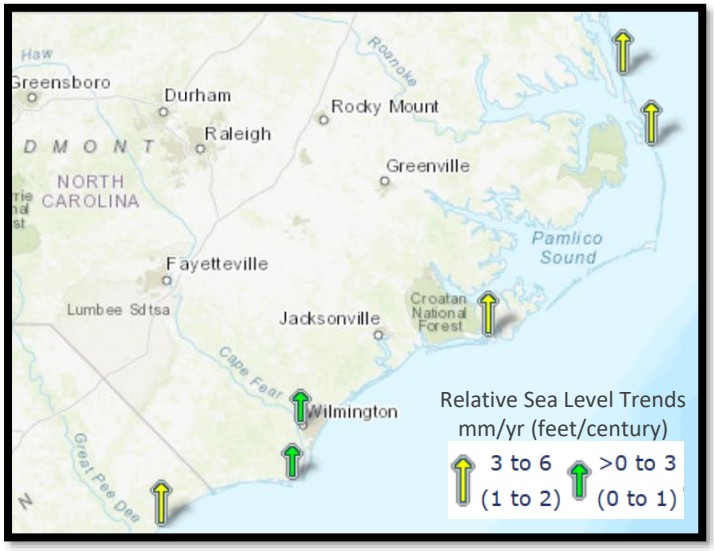


Note: 2010 data only represents through 2015; (developed based on data from NOAA)[25]

Where are we Today?

Coastal Region: Sea Level Rise

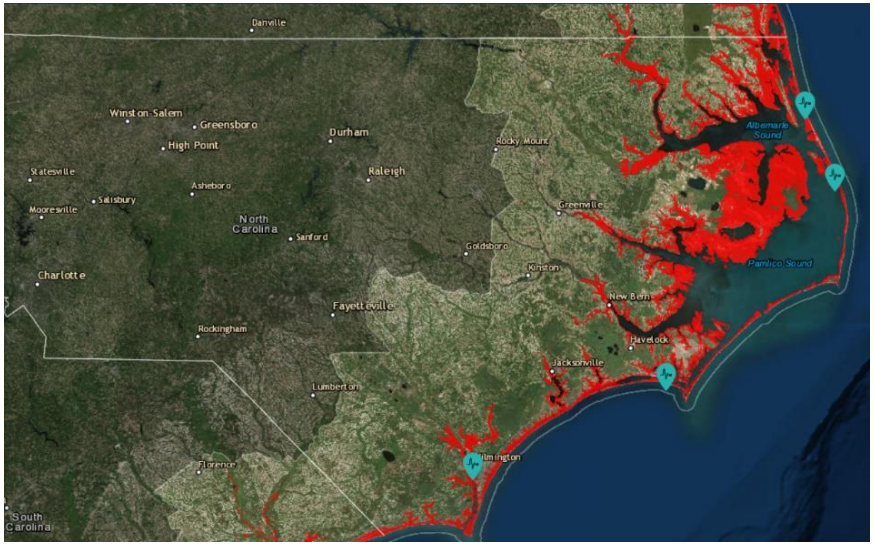
The N.C. coastline has experienced a *similar to accelerated* sea level rise compared to global averages (global mean sea level has risen about 7 to 8 inches since 1900).[9]



- Similar to global mean sea level are the tide gages in green, estimating a rise of about a 2 mm/year (from the 1930s).[10]
- Accelerated rise compared to global mean sea level are the tide gages in yellow, with about a 3 to 4.6 mm/year (from the 1950s and 1970s). [10]

More than 2,300 miles of coastline is susceptible to 1 meter rise, with increasing vulnerability in response to loss of coastal wetlands (mechanisms for natural protection).[11]

Impacts on Roads and Bridges: Includes inundation of roads, frequent or severe flooding, erosion of road base and bridge supports, and loss of barrier shoreline.[16]

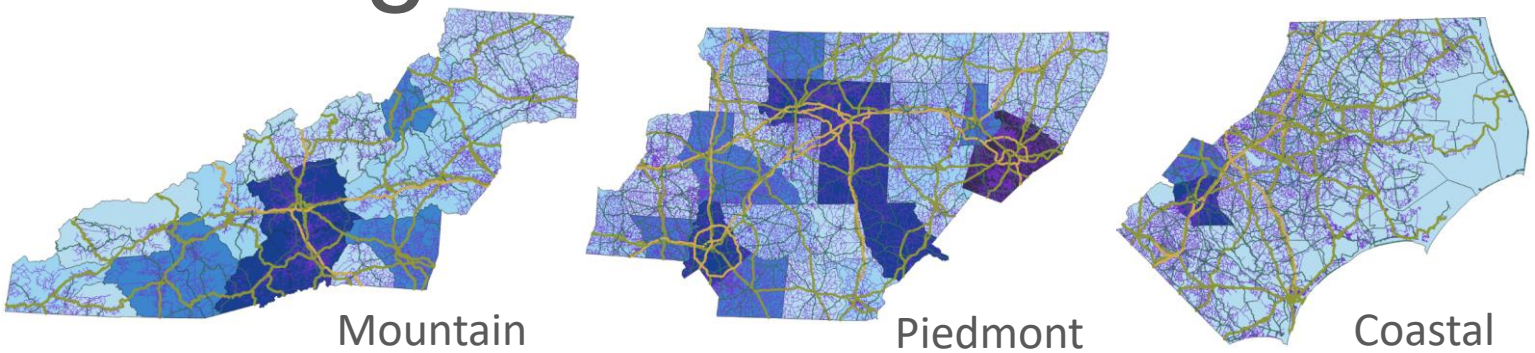


Areas in red are currently subject to tidal flooding, also called “recurrent” or “nuisance” or “sunny-day” flooding.[12]

Examples of past events and activities:

- NC 12 was overtopped under a recent exceptionally high tide.[1]
- Wilmington, N.C. underwent an infrastructure sea level rise resilience study, supported by EPA.[6]

High Risk of Dam Failure



Source: WSP developed GIS maps based on Figure 3-26 in NCDPS Enhanced Mitigation Plan[21] and NCDOT on-line NCRouteArcs GIS data.[23]

- A dam failure leads to significant downstream infrastructure damage and loss of life.[21]
- The most common dam failures include overtopping, erosion of earth spillways and overstressing the dam. Maintenance is critical to reduce failure susceptibility. [21]
- There are more than 5,600 dams in N.C. with 1,429 dams identified as high risk, posing significant risk to public safety and property if dam failure were to occur. [21]

North Carolina Dam Break Events

#	Event	Year	Location	Severity	Extent of Damages
1	Bearwallow Lake Dam Break	1976	Bearwallow Lake, N.C.	Sliding	Unknown
2	Potato Hill Lake Dam Break	1977	Potato Hill Lake, N.C.	Overtopping	Unknown
3	Winston Dam Break	1912	Winston, N.C.	Overtopping	Unknown
5	Hurricane Fran	1996	Eastern N.C.	3 major and 12 minor breaks	Private facilities
6	Hurricane Floyd	1999	44 Counties of N.C.	36 failures	100 dams damaged; hog lagoon overflow
7	Hope Mills	2003	Hoke and Cumberland Counties, N.C.	5 failures and 11 damaged dams	No injuries
8	Hurricane Matthew	2016	Cumberland, Duplin, Harnett, Hoke, Lenoir, Sampson, Wayne and Wilson Counties	12 state-regulated dams breached, 8 other, non-regulated dams breached	400 inspections conducted after the event

Source: NCDPS[21]

Where are we Today?

Past Events have Shown…

Contracting Challenges

- Hurricane Florence had approximately 3,400 sites and 2,400 roads with damage to highway infrastructure, requiring state forces to do emergency repairs. This also required a lot of staff time for contracting for more permanent repairs.[5] Hurricane Michael had additional impacts.
- Snow removal during N.C. snow events is generally done in-house, but it can be a struggle to find snow and ice contractors for additional services (contractors do not consider it worth the capital investment). [5]

Locations historically impacted by Flood

- Specific highways can be repeatedly problematic during flood conditions (e.g., washouts along I-40, US-70 towards the coast, major routes to the coast).[1,5]
- The larger issue tends to be erosion of road approaches to the bridges, not the integrity of the bridge.[19]

Need for Monitoring Assets

- There is a need to continuously monitor bridges that were designed without today's society in mind (e.g., much older bridges were not designed with today's truck loads in mind, which causes impacts on bridge condition).[19]

NCDOT Practices

Understanding and Assessing Hazards

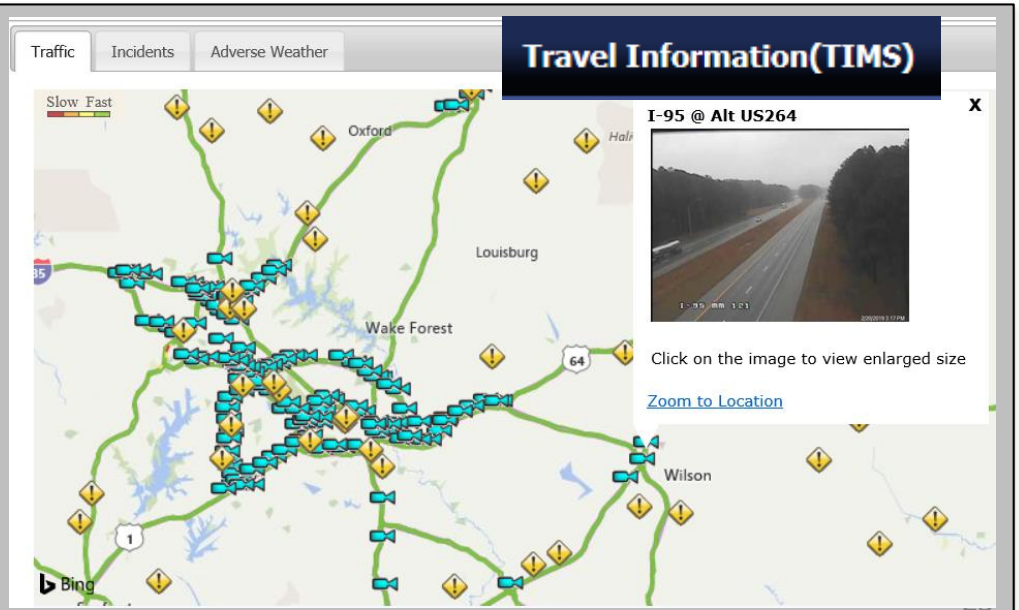
- There is a good amount of data and local ground knowledge regarding flooding conditions.[1,3] Emergency managers in the field know historical issues and are available to support hazard modeling by ground truthing the results of model simulations.[3]
- NC Department of Public Safety (NCDPS) developed the Enhanced Mitigation Plan that outlines current and future hazards across the state, as well as mitigation opportunities to enhance response and recovery efforts.[3]
- NCDOT is aware of storm surge data and analysis that is ongoing to help identify coastal flood vulnerabilities.[1] Elevation data (e.g., LiDAR) is available for the entire state and building footprint.[3] NCDOT is also assessing river basin tools for forecasting.[1]
- NCDPS is currently working with counties to review and potentially revise evacuation zones.[3]

NCDOT Practices

Communicating Hazards to the Public in Real-Time

- During an event, online data tools from NCDOT and NC Emergency Management (NCEM) are available for the public to monitor driving hazards. In addition, a call center is available.[27]
- WAZE and other GPS/ Navigation providers ingest data from DriveNC.gov to provide information to their customers (e.g., removing a segment of a route that is flooded from the WAZE application).[3,27]

NCDOT also provides travel information in real-time[29]

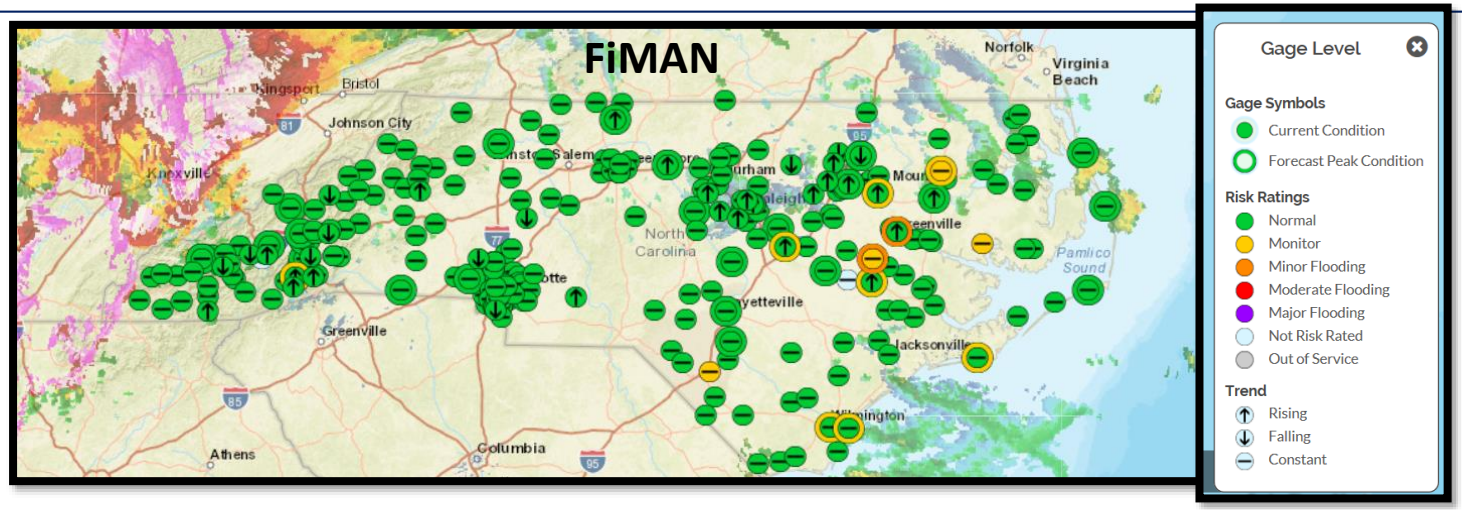


Where are we Today?

NCDOT Practices

Emerging NCDOT Tools and Collaboration during Response and Recovery

- A strong relationship between NCDPS and NCDOT has been built as a result of recent events.[5] This can be leveraged to further tease out transportation vulnerabilities under preparedness and scenario analyses.
- Using new technology such as the ESRI Survey 1-2-3 app, field personnel can quickly upload damage assessment information (for instantaneous recording). [5]
- The Disaster SharePoint Site has been extremely useful in managing real-time events.[5]
- NCDOT's real-time website monitors road closures and NC Flood Inundation Mapping and Alert Network (FiMAN) identifies when the water elevation is low enough for bridge repair. [19]



Where are we Today?

Source: NC Flood Inundation Mapping and Alert Network (FiMAN)[30]

NCDOT Practices

NCDOT Hazard Mitigation

- NCDOT has some project success with FEMA supporting betterments (i.e., re-building an asset for resiliency, as opposed to building back to the way it was).[1]
- In a past project, NCDOT raised the bridge elevation to account for flood waters (e.g., a bridge along NC12 was designed for higher elevation in response to sea level rise).[19]
- There is a movement towards building joint-less bridges as much as possible to reduce brine impacts that occur after winter storms (i.e., concrete bridges narrower than 400 feet and steel bridges narrower than 300 feet). [19]
- Overall, bridges are better designed for flood conditions. Engineers take design values and add in safety factors that provide a buffer, so generally bridges have held up well to past storms. Also, wave modeling at high tide helps to inform the elevation design of coastal bridges. [19]

WHERE WE ARE GOING

Projected Hazards

- **Floods:** Extreme precipitation is projected to increase under a warming atmosphere, which may lead to more flash flooding.[8]
- **Winter Storms:** The projected change in winter storms is unclear. This is based on varying findings on enhanced arctic warming and the associated impacts on amplifying the jet stream during winter months.[8]
- **Wildfire**: There is an increase in the projected risk for large wildfires for portions of the state.[13]
- **Earthquakes:** There are no changes expected in the future likelihood of earthquakes.

Projected Hazards

- **Tornadoes:** Since 2000, observations in the United States suggest tornado activity days have decreased while the number of tornadoes has increased. The projections suggest an increase in the frequency and intensity of severe thunderstorms, which may affect tornadic activity. [8]
- **Hurricanes**: Projections suggest events will be more frequent with an increase in major hurricanes with higher rainfall rates (note changes in the storm track is challenging to project with confidence).[8] Projections of changes in hurricanes is particularly important given hurricanes have become a primary driver of significant regional flooding over the past decade in North Carolina.
- **Heat Events:** Extremely warm days are expected to increase even more than average temperatures.[17]
- **Dam Failures**: No changes in future likelihood found.

Projected Hazards: Sea Level

U.S. Interagency Sea Level Rise Task Force recommended these scenarios:[14]

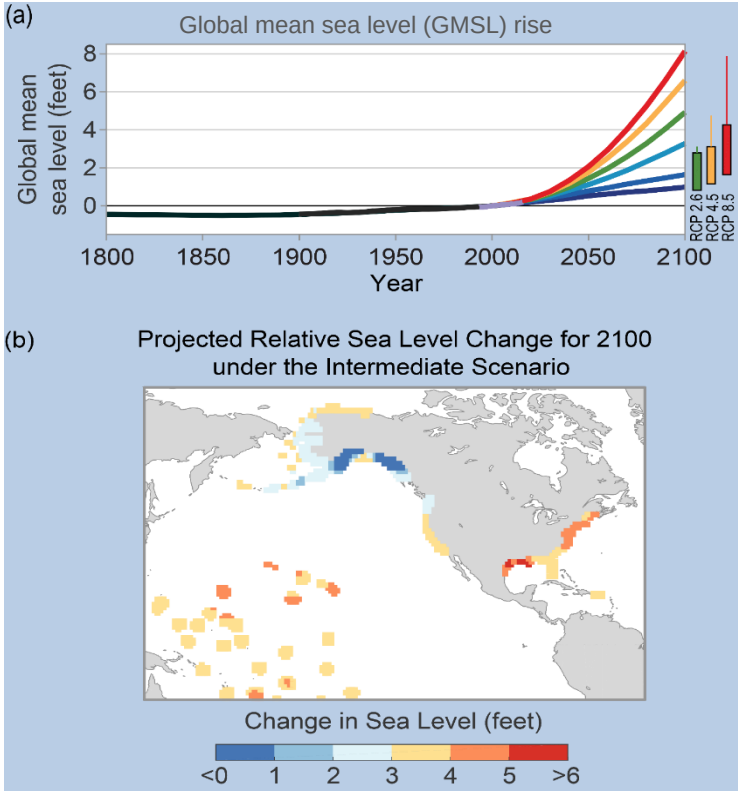
- Lowest scenario (navy blue curve) is simply an extrapolation of the current trend of 0.12 inches per year of rise to an estimated 1 foot of rise by 2100.
- The other five scenarios suggest a sea level rise of 1.6 to 8.2 feet by 2100, or a rise of 0.2 inches to 1.7 inches per year.

North Carolina coastline is **likely to experience sea level rise at or above the global mean sea level**. The table below is sea level rise projections for Wilmington, N.C. tide gage relative to 2000 based on NOAA's recently released sea level rise projections.[9] By 2050, sea level may rise near to above 3 feet.

Year	Low	Intermediate	High	Extreme
2020	0.26	0.49	0.72	0.79
2030	0.43	0.79	1.31	1.44
2040	0.56	1.05	1.94	2.2
2050	0.69	1.44	2.69	3.22

Source: USACE[26]

Note that the higher scenarios are considered physically plausible and it's important to recognize that sea level will continue to rise well past 2100. This also assumes minimal reduction in the Antarctica ice sheet.

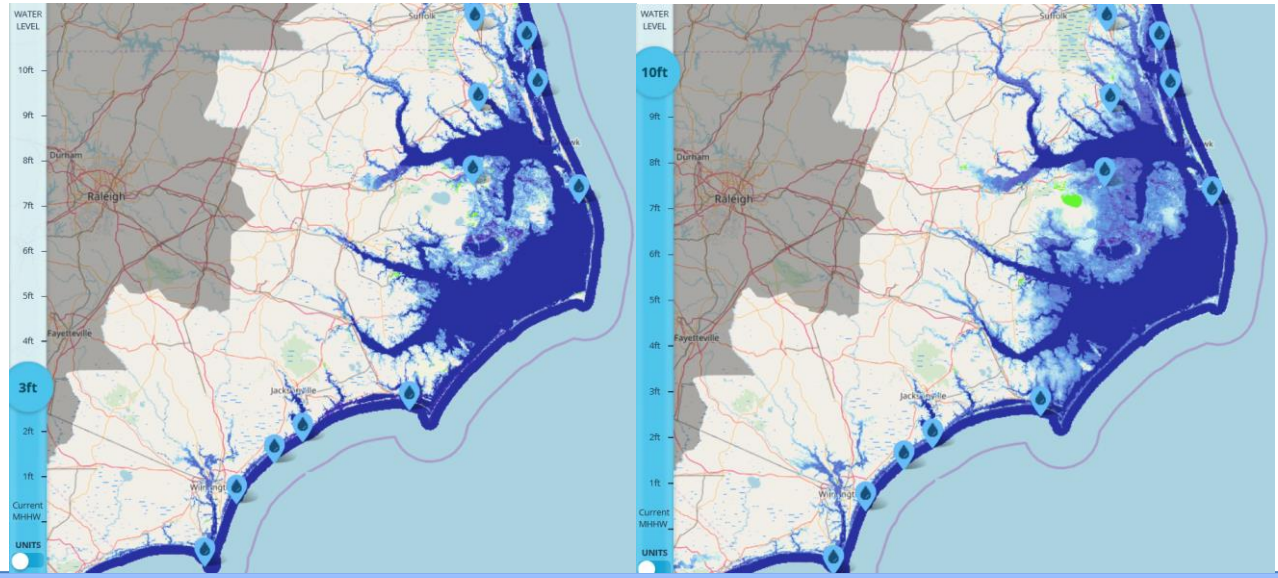


Global mean sea level (GMSL) rise - the six Interagency GMSL scenarios (navy blue, royal blue, cyan, green, orange, and red curves), the *very likely* ranges in 2100 for different RCPs (colored boxes), and lines augmenting the *very likely* ranges by the difference between various projections of the median Antarctic contribution. (b) Relative sea level (RSL) rise (feet) in 2100 projected for the Interagency Intermediate Scenario (1-meter [3.3 feet] GMSL rise by 2100) (Figure source: Sweet et al. 2017).[9]

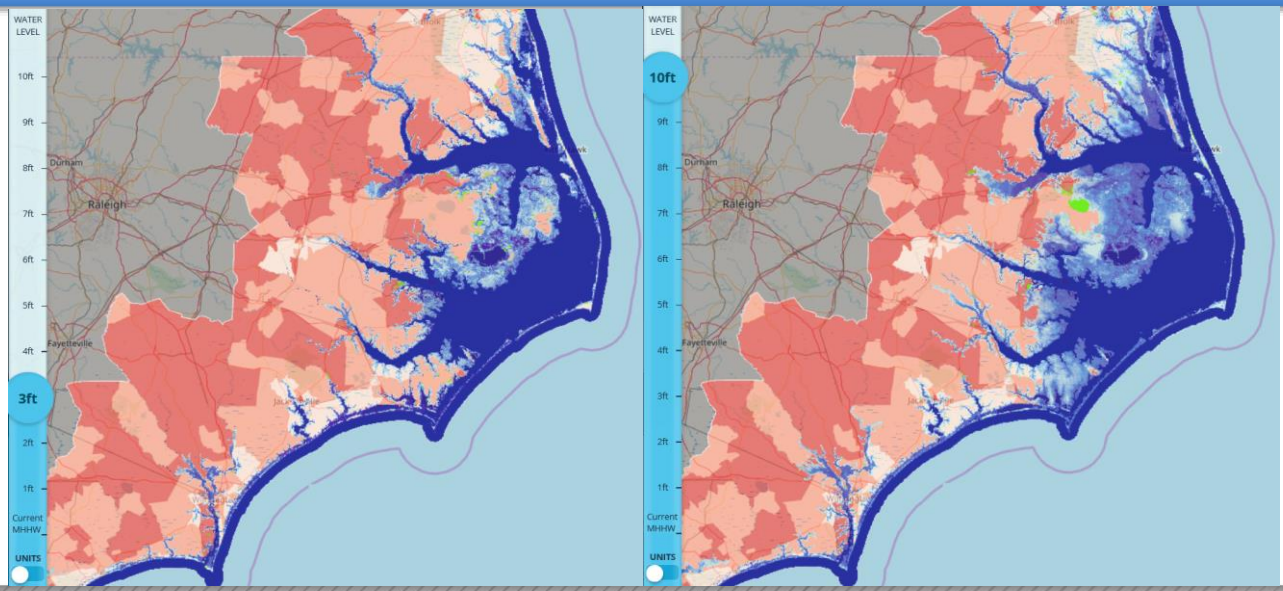
Coastline Vulnerable to Rising Seas

These maps show the major roads that may be inundated under 3 feet and 10 feet of sea level rise.[12]

Note: The areas shaded in grey are inland areas that are not included in NOAA's modeling.



These maps identify areas with high community social vulnerability (darker shading) that are also more susceptible to flooding.[12]



FINDINGS AND FUTURE DIRECTION FOR NORTH CAROLINA

Forward Thinking

Noticed Trends

- Recent hurricane activity has become increasingly costly with multiple impacts on transportation users (some communities were isolated and required supplies dropped by helicopter).[3]
- The frequency, intensity and/or magnitude of some hazards has increased over the past few decades, with projections suggesting this could continue over the coming century.[6]

Needs

- Current practice of monitoring bridges for scour should continue, as well as providing bed material elevation to prevent scour when bridges are built over stream crossings.[19]
- There is a need to understand the interdependencies between transportation and electricity, and the consequences on communities.[6]
- There is considerable data available to mine and analyze how to collectively present in an informative way that is understandable and supports actionable results.[1,6]
- There is a desire to move towards new materials for bridges that last longer than concrete and steel, and are less vulnerable.[19]

Emergency Planning

Nexus of Emergency Planning and Long-term Transportation Planning

- Continued integration of utilizing emergency planning tools and resources (including real-time data) during hazardous events.
- Continued documentation of costs associated with events to gauge hazards of greatest financial impact on NCDOT and its mission.

Collaboration and Coordination

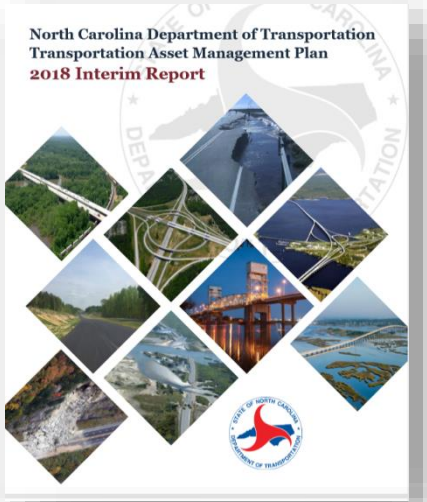
- NCDOT and NCDPS staff spoke highly of successful cross-coordination efforts of response and recovery during recent storms. Continued support to ensure strong collaboration during an emergency is highly recommended.
- There is a need for internal collaboration with staff across NCDOT departments to identify agency, program, and project level risks associated with environmental hazards (consistent with the objectives of NCDOT TAMP requirements).
- Targeted NCDOT coordination is needed with community stakeholders to identify critical and vulnerable transportation corridors to support project prioritization and investment analysis.

Kinston, N.C., shows flooding Sept. 14, 2018 in Lenoir Count

Hurricane Matthew around Selma, North Carolina, October 12, 2016. ***North Carolina National Guard***

Project Prioritization & Investments

- NCDOT continues to build and support risk analysis for NCDOT TAMP (covers more than just environmental hazards).
- Continue to build and test the GIS exposure data that potentially stress the NCDOT system.
- Develop and conduct a robust risk-based assessment that can inform decision makers in making appropriate transportation investments. This takes into account the impacts of loss of transportation operations on communities, tourism, freight, etc.
- Future research to provide transportation-targeted climate projections and to quantify hazard-to-damage relationships for highways and bridges.
- Develop performance metrics and monitor schedules to revisit and calibrate for future success.



Construction on I-85 bridge over Yadkin river. ***NCDOT (2011)***

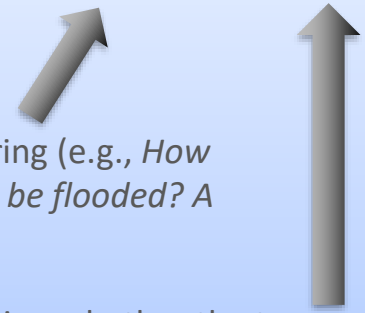
Assess Future Hazards & Risks

Based on NCDOT data, modeling capabilities and efforts, and depth of institutional knowledge of "hot spots" vulnerabilities…

NCDOT has the building blocks to conduct an Advanced Hazard and Risk Analysis. Risk analysis is the preferred method when there is inherent uncertainty that needs to be incorporated:

- **Risk Analysis Informs**: project prioritization, investment strategies, the required risk management chapter in the NCDOT Transportation Asset Management Plan (TAMP), and evaluations from system-scale resilience strategies to project-scale adaptation options.

Risk = Hazard x System/Asset Impact x Consequences



Likelihood of the hazard occurring (e.g., *How likely is it that this location will be flooded? A wildfire will occur?)*

Determine whether the transportation system or facility is exposed to the hazard and, if so, the probability of failure or disruption (e.g., *Is the roadway exposed to flooding under the flood scenario?)*

Determine if there are adverse effects (e.g., *costs to repair/replace; additional maintenance costs; indirect costs; induced costs; other non-financial consequences)*

Advanced Hazard and Risk Analysis

First, screen NCDOT assets and prioritize assets based on risks (system-scale)

Repeat Steps A and B for baseline ("today") analysis and future scenario analyses (accounting for associated uncertainties)

A. Identify NCDOT Assets At-Risk

B. Estimate Consequence of System Disruptions Caused by At-Risk Assets

C. Prioritize Critical At-Risk NCDOT Assets

Second, assess critical at-risk assets for mitigation strategies to environmental hazards (generally at the project-scale)

D. Risk-Based Engineering Assessment of Each Critical At-Risk Asset

E. Assess Performance anticipated with Mitigation Strategies

F. Recommendation of Best Mitigation Approaches for Each Critical Asset for Effective Investment

Third, take action

Source: WSP 2019[18]

APPENDICES

End Note Sources

1. NCDOT Hydraulics Unit. Interview with Matthew Lauffer and John Twisdale on 1/25/2019.
2. Wooten, R.M., Cattanach, B.L., Bozdog, G.N., Isard, S.J., Fuemmeler, S.J., Bauer, J.B., Douglas, T.J. The North Carolina Geological Survey's Response to Landslide Events: Methods, Findings, Lessons Learned, and Challenges. 3rd North American Symposium on Landslides, Roanoke, VA, June 4-8, 2017. https://files.nc.gov/ncdeq/Energy%20Mineral%20and%20Land%20Resources/Geological%20Survey/Landslide_reports/2017_NASL_NCGS_Response%20to%20Landslides_Wooten%20et%20al.published.pdf
3. NC Department of Public Safety, Division of Emergency Management. Corey Johnson, Deputy Chief, on 1/22/2019.
4. https://www.charlotteobserver.com/news/local/article212169229.html
5. NCDOT, Emily McGraw, State Maintenance Engineer, on 1/25/2019.
6. NC Sea Grant College Program, Susan White, Executive Director, on 1/25/2019.
7. NOAA National Hurricane Center
8. Kossin, J.P., T. Hall, T. Knutson, K.E. Kunkel, R.J. Trapp, D.E. Waliser, and M.F. Wehner, 2017: Extreme storms. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 257-276, doi: 10.7930/J07S7KXX.
9. Sweet et al. 2017. Global and regional sea level rise scenarios for the United States. https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf
10. NOAA Historic trends for local tide gage data
11. NEMAC. A Regional Perspective of North Carolina.
12. NOAA Sea Level Rise Viewer.
13. Bell, J.E., S.C. Herring, L. Jantarasami, C. Adrianopoli, K. Benedict, K. Conlon, V. Escobar, J. Hess, J. Luvall, C.P. Garcia-Pando, D. Quattrochi, J. Runkle, and C.J. Schreck, III, 2016: Ch. 4: Impacts of Extreme Events on Human Health. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC, 99–128. http://dx.doi.org/10.7930/J0BZ63ZV
14. NOAA 2017. U.S. Interagency Sea Level Rise Task Force.
15. FEMA 2003. Risk Management Series: Reference Manual. FEMA 426.
16. Climate Ready North Carolina Building: A Resilient Future (2012).
17. Vose, R.S., D.R. Easterling, K.E. Kunkel, A.N. LeGrande, and M.F. Wehner, 2017: Temperature changes in the United States. In: *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 185-206, doi: 10.7930/J0N29V45.

End Note Sources

18. WSP 2019. Advanced Hazard and Risk Analysis for Transportation Practitioners. White Paper. (In Progress)
19. NCDOT Structures Management Unit. Interview with Brian Hanks on 2/5/2019.
20. NOAA National Hurricane Center, Storm Surge Overview.
21. NCDPS Enhanced Mitigation Plan
22. NOAA NWS Heat Index
23. NCDOT on-line NCRouteArcs GIS data, https://connect.ncdot.gov/resources/gis/Pages/GIS-Data-Layers.aspx
24. USGS, https://earthquake.usgs.gov/earthquakes/byregion/northcarolina.php
25. NOAA, https://www.aoml.noaa.gov/hrd/tcfaq/E11.html
26. USACE Sea Level Rise Calculator, http://corpsmapu.usace.army.mil/rccinfo/slc/slcc_calc.html
27. Email communications with Kelly Wells, Traveler Info Engineer, NCDOT (April 12, 2019).
28. National Hurricane Center (NHC), www.aoml.noaa.gov/hrd/tcfaq/E11.html
29. NCDOT Travel time, https://www.ncdot.gov/travel-maps/traffic-travel/Pages/default.aspx
30. NC Flood Inundation Mapping and Alert Network (FiMAN), https://fiman.nc.gov/About.aspx
31. Patrick Norman, Director of Highway Operations, on 5/31/2019

Appendix

Summary of Interviews

- Corey Johnson, Deputy Director for Planning, Planning & Homeland Security Deputy Chief, NC Department of Public Safety, Division of Emergency Management
- Matthew (Matt) Lauffer, PE, CPM, Assistant State Hydraulics Engineer, Hydraulics Unit, North Carolina Department of Transportation
- John (Jay)Twisdale, PE, Assistant State Hydraulics Engineer, Hydraulics Unit, North Carolina Department of Transportation
- Susan White, PhD, Executive Director, NC Sea Grant College Program; Director, Water Resources Research Institute of UNC; Director, NC Space Grant
- Emily McGraw, P.E., State Maintenance Engineer, North Carolina Department of Transportation
- Brian Hanks, P.E., State Structures Engineer, Structures Management Unit, North Carolina Department of Transportation

NC Preparedness Plans

Plan	Description
NC Hurricane Guide (2017)	Preparedness and evacuation information, including tips on road safety.
NC Emergency Preparedness Initiative and Blueprint (2014)	Plan for a whole community emergency preparedness Transportation Plan: 1. Identify and inventory equipment that enhances transport accessibility, including people with disabilities. 2. Develop intake materials to document passengers and personal effects, including durable medical equipment. 3. Provide training on security and handling of durable medical equipment, including liability issues.
NC Enhanced Hazard Mitigation Plan (2018)	Details responsibilities in emergency management and across NC agencies, lists risk parameters of a number of hazards and threats, assesses vulnerabilities, mitigation capabilities and planning and continued monitoring of the plan and progress.
Climate Ready North Carolina: Building a Resilient Future (2012)	Summarizes general trends in climate hazards observed and projected, conducted a high-level vulnerability analysis and provided recommendations for cross-sector and sector-specific climate adaptation planning.

Appendix